Producing Radioactive Ion Beams

through the Isotope Separation On Line Method:

Advances, challenges and opportunities.

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ISOL: The Oxford Dictionary of Abbreviations | 1998 | **isol.** isolate(d) • isolation

My definition of the ISOL method:
the production of a (pencil-like) beam of (short-living) nuclei,
stopped after the nuclear reaction (or decay),
(re-)ionized,
mass separated,
all in a efficient, fast flow.

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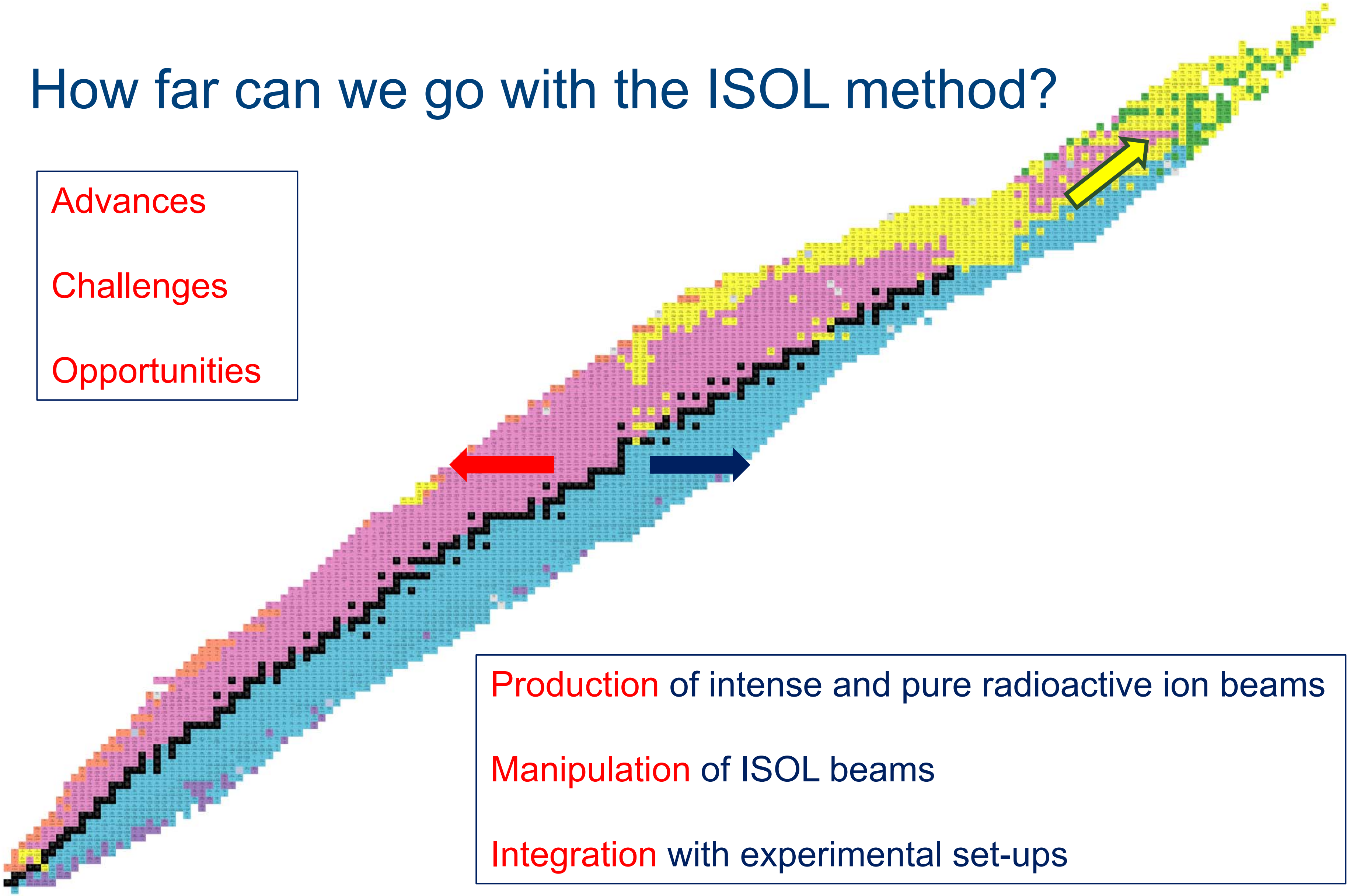
How far can we go with the ISOL method?

Advances

Challenges

Opportunities

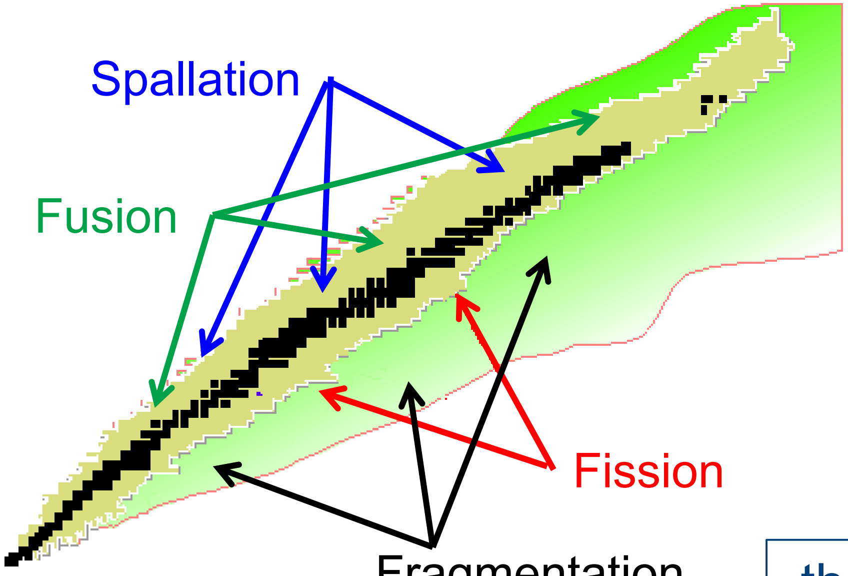


Production of intense and pure radioactive ion beams

Manipulation of ISOL beams

Integration with experimental set-ups

Production of intense and pure radioactive ion beams



Choice of the reaction

- intensity of primary beam
- target thickness
- cross section
- selectivity of the reaction

Purification **In Flight (IF)** or after stopping → **ISOL**

thick target <=> thin target

solid catcher

diffusion out of the target or catcher
transfer to the ion source
Z & $T_{1/2}$ dependence

ion source
Z selection

mass separator

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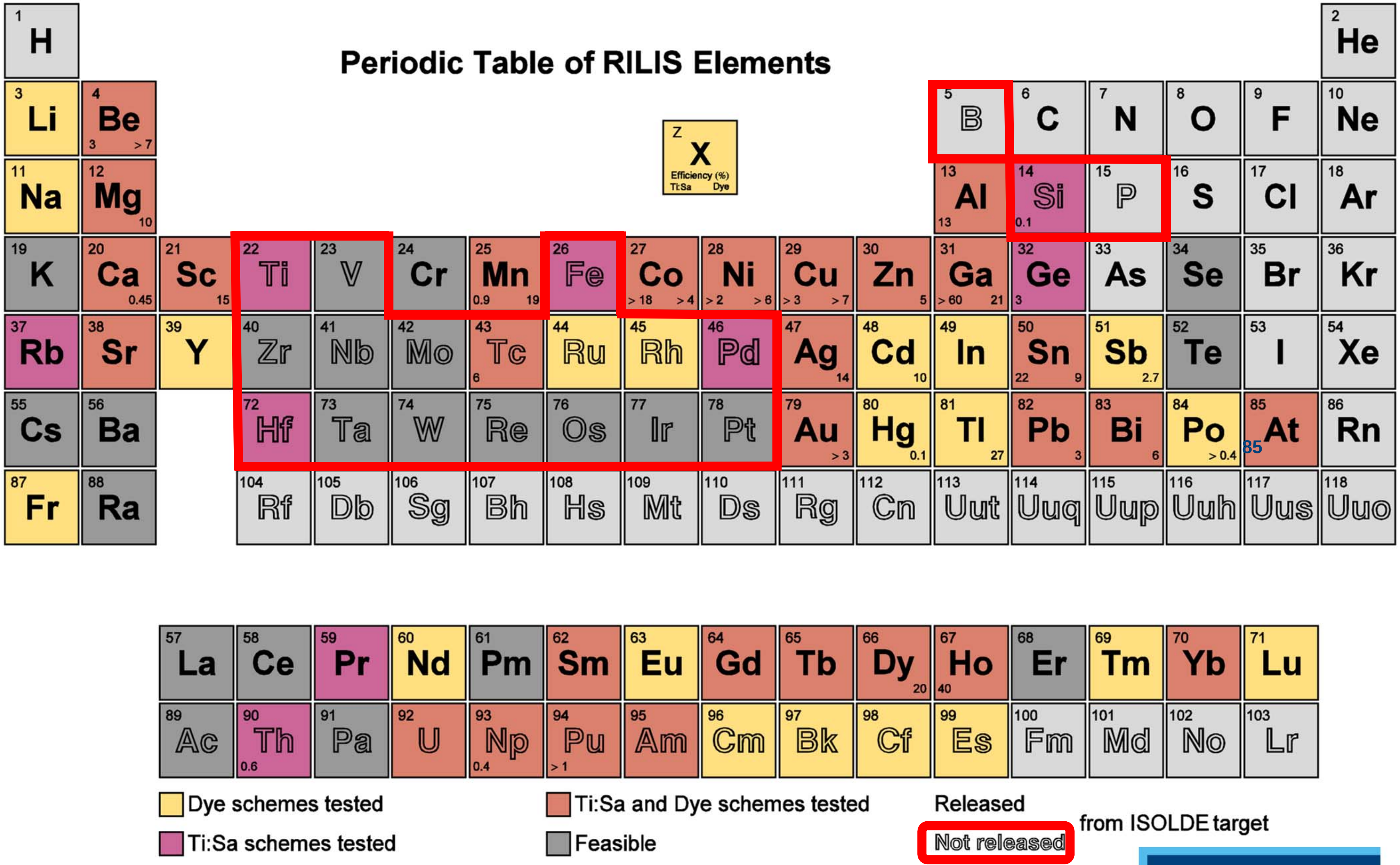
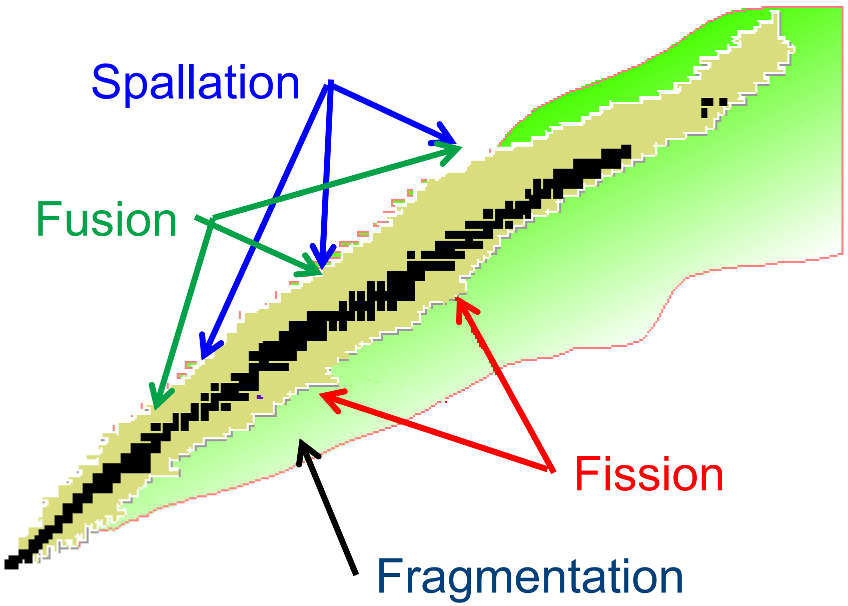
Challenge: the release problem



courtesy B. Marsh

Production of intense and pure radioactive ion beams



Choice of the reaction

- intensity of primary beam
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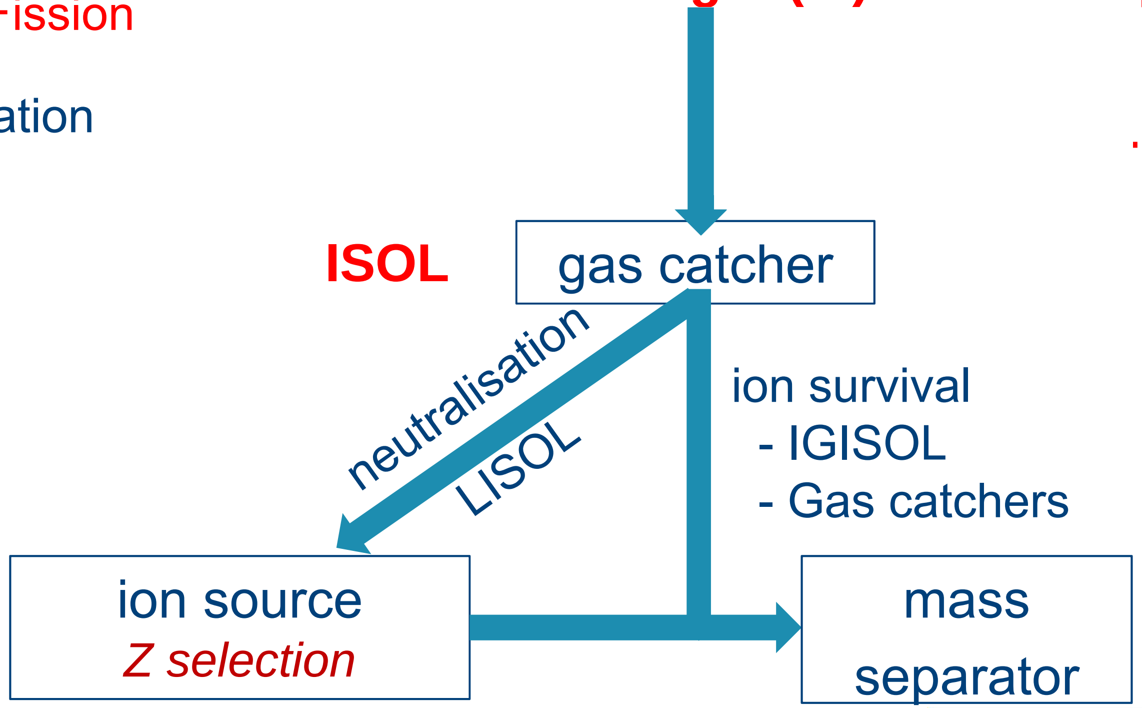
Purification **in flight (IF)** or after stopping



Production: Target Ion Source Developments

Primary beam intensity

Higher in primary beam intensity (now 100 μA at ISAC)
From kW towards MW on target

Recent developments of target and ion sources to produce ISOL beams

T. Stora Nuclear Instruments and Methods in Physics Research B 317 (2013) 402–410

CERN, CH-1211 Geneva 23, Switzerland

Release

=> molecular sidebands

HELICON-type ion source for molecular sidebands

M. Kronberger et al. / Nuclear Instruments and Methods in Physics Research B 317 (2013) 438–441

50-fold enhancement of $^{10-11}CO^{+}$ with nanostructured CaO target

Fast release **=>$T_{1/2}$**

=> nanostructured materials

J.P. Ramos et al. / Nuclear Instruments and Methods in Physics Research B 320 (2014) 83–88

fast diffusing => shorter $T_{1/2}$
lower temperatures => higher reliability

Selectivity

=> lasers and physico-chemical properties

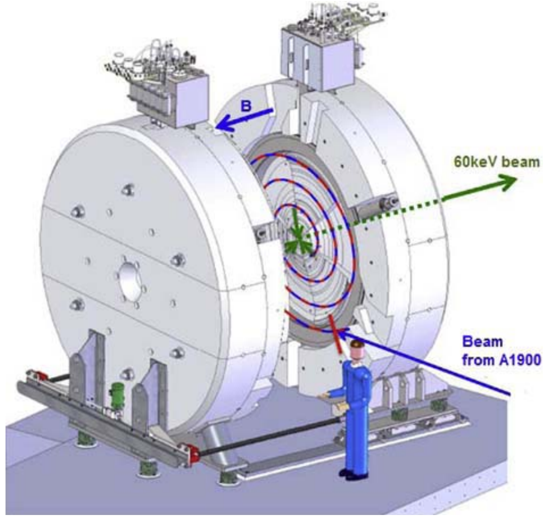
Production: Gas stoppers for high-energy recoils

Challenge: large stopping volume is needed

=> minimize neutralization, diffusion losses and delay times using electric fields

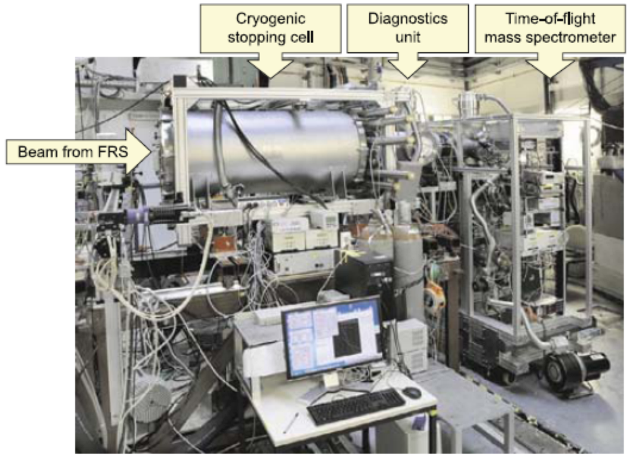
- Linear gas stoppers

  M. Wada, NIM B317 (2013) 450-456



- Circular gas stoppers

  S. Schwarz et al., NIM B317 (2013) 463-467



Challenges: beam purity and high intensity

=> cryogenic cell

W. R. Plaβ et al., NIM B317 (2013) 457-4612

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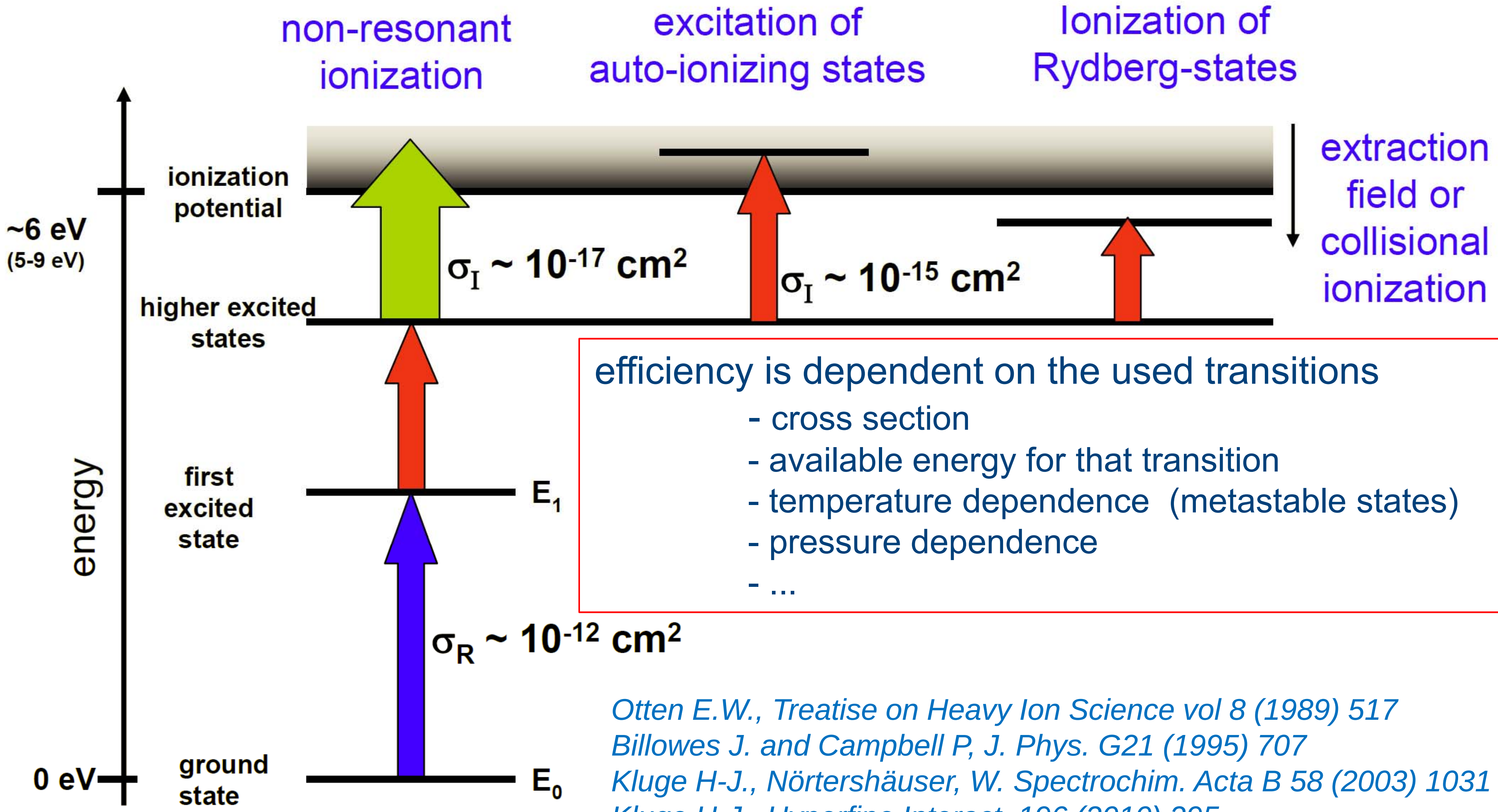
Production: Resonant Ionization Laser Ion Source (RILIS)



efficiency is dependent on the used transitions

- cross section
- available energy for that transition
- temperature dependence (metastable states)
- pressure dependence
- ...

courtesy I. Moore

Otten E.W., Treatise on Heavy Ion Science vol 8 (1989) 517
Billowes J. and Campbell P, J. Phys. G21 (1995) 707
Kluge H-J., Nörtershäuser, W. Spectrochim. Acta B 58 (2003) 1031
Kluge H-J., Hyperfine Interact. 196 (2010) 295
Cheal B. and Flanagan K., J. Phys. G. 37 (2010) 113101

Manipulation of ISOL beams

- cooling
- bunching

=> improving the ion optical properties

- mass separation => optimal mass-resolving power while keeping the efficiency (dipoles M/ΔM ~20.000; cyclotrons and MR-TOF's higher)
- neutralisation => for laser applications
- polarisation => solid-state physics, fundamental physics
- deceleration => injection in traps
- post acceleration => reactions, implantation, …

Manipulation: Post acceleration

Challenge: higher charge state is needed for efficient post acceleration

P. Delahaye / Nuclear Instruments and Methods in Physics Research B 317 (2013) 389–394

=> stripper foils
    TRIUMF / ISAC

=> Electron Cyclotron Resonance Ion Source (ECRIS)
    LLN
    TRIUMF / ISAC
    GANIL / SPIRAL

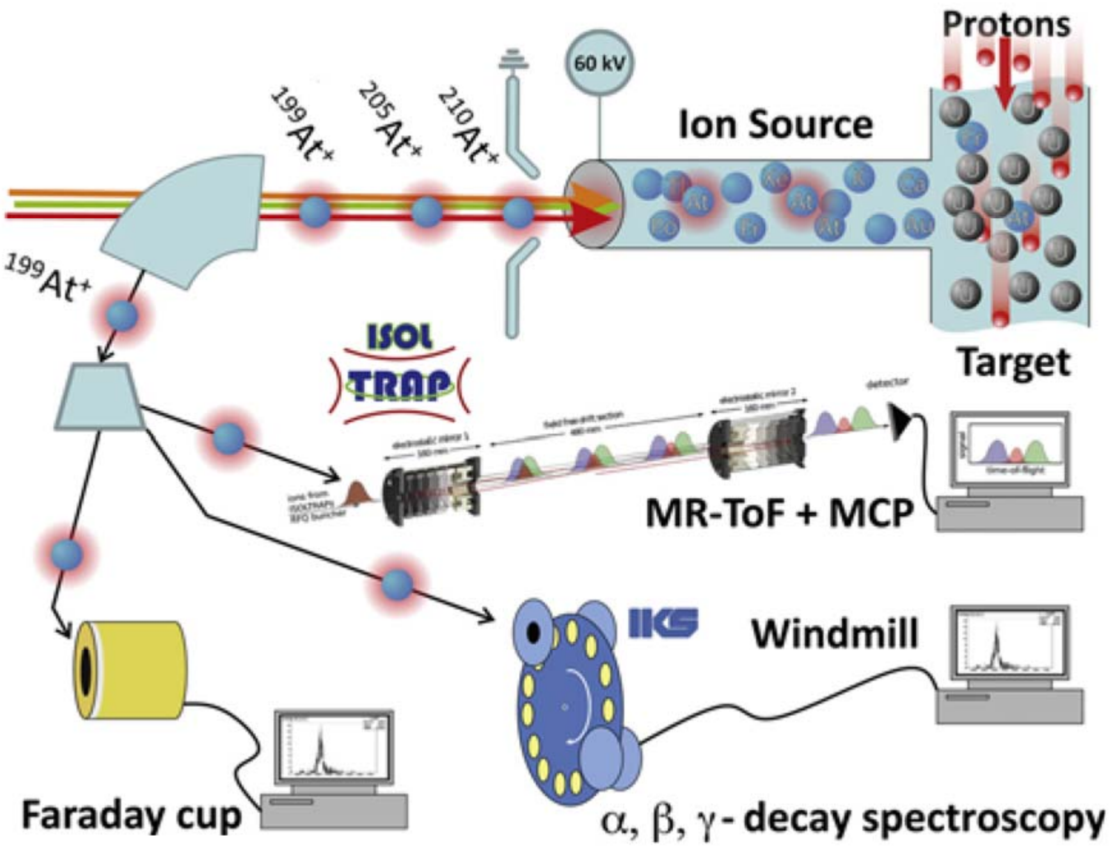
=> Electron Beam Ion Source or Trap (EBIS/T)
    ISOLDE => HIE-ISOLDE
    NSCL
    + more to come

Integration with experimental set-ups

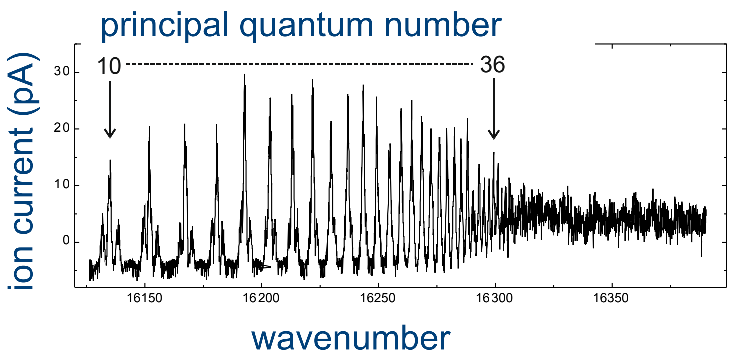
- decay setups
  - different implantation conditions (temperature, material, e.m. fields, …)
  - different detectors
- laser setups
- ion traps
- atom traps
- reaction chambers
- spectrometers
- storage rings

Strong coupling between the production, the manipulation and the experiments

Integration: In-Source Laser Production and Spectroscopy



B. A. Marsh et al.
NIMB 317 (2013) 550-556

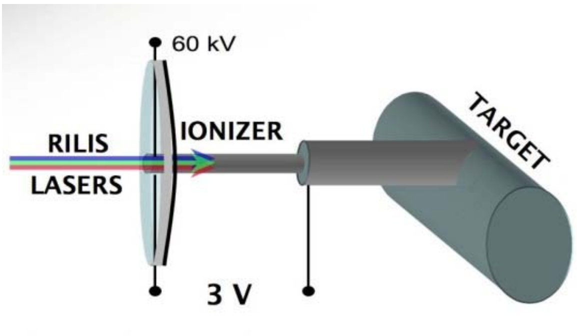


IP(At) = 9.31751(8) eV

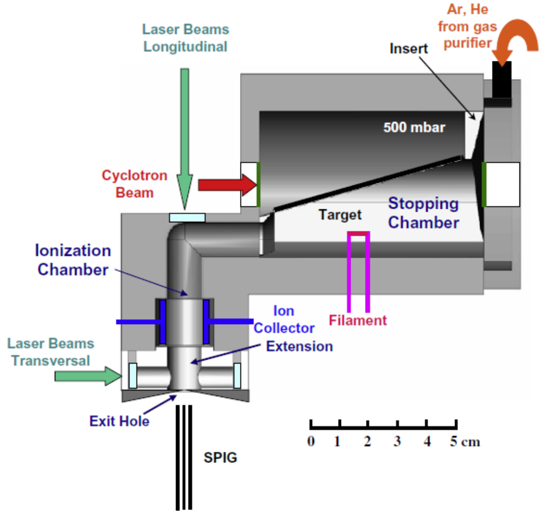
S. Rothe et al., Nature Com. (2013) DOI 10.1038

Integration: In-Source Laser Spectroscopy

Hot Cavity @ IRIS, ISOLDE, TRIUMF, ...



In-Gas Cell @ LISOL



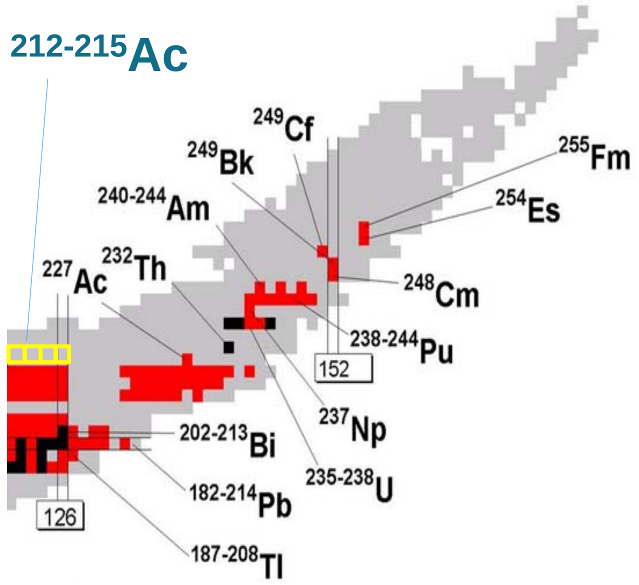
➢ Hot Cavity

- (Almost) no refractory elements
- $T_{1/2}$ element dependent
- Sensitivity 1 ion/s (^{182}Pb)
- Resol~ 4 GHz (^{59}Cu) (Doppler)
- Produced Ion beams ~30 elements

➢ Gas Cell

- All elements available
- $T_{1/2}$ cell evacuation time
- Sensitivity < 1 ion/s (^{97}Ag)
- Resol. ~ 4 GHz (^{59}Cu) (Pressure)
- Produced Ion beams ~15 elements

Integration: In-Gas-Cell Laser Spectrocopy



K. Blaum et al., Phys. Scr. T152 (2013) 014017

After forty years of faithful service
LISOL's last experiments

in a new region

^{197}Au(^{20}Ne-145 MeV,4-5n)^{212,213}Ac

^{197}Au(^{22}Ne-143 MeV,4-5n)^{214,215}Ac

and with a large collaboration

LISOL: P. Creemers, L.P. Gaffney, L. Ghys, C. Granados, M. Huyse, Yu. Kudryavtsev,
Y. Martínez, E. Mogilevskiy, S. Raeder, S. Sels, P. Van den Bergh, P. Van Duppen, A. Zadvornaya

GANIL- IPN Orsay – LPC Caen: B. Bastin, D. Boilley, Ph. Dambre, P. Delahaye, P. Duchesne, X. Fléchard, S. Franchoo, N. Lecesne, H. Lu, F. Lutton, Y. Merrer, B. Osmond, J. Piot , O. Pochon, H. Savajols , J. C. Thomas, E. Traykov

University of Mainz: R. Heinke, T. Kron, P. Nauberreit, P. Schoenberg, K. Wendt

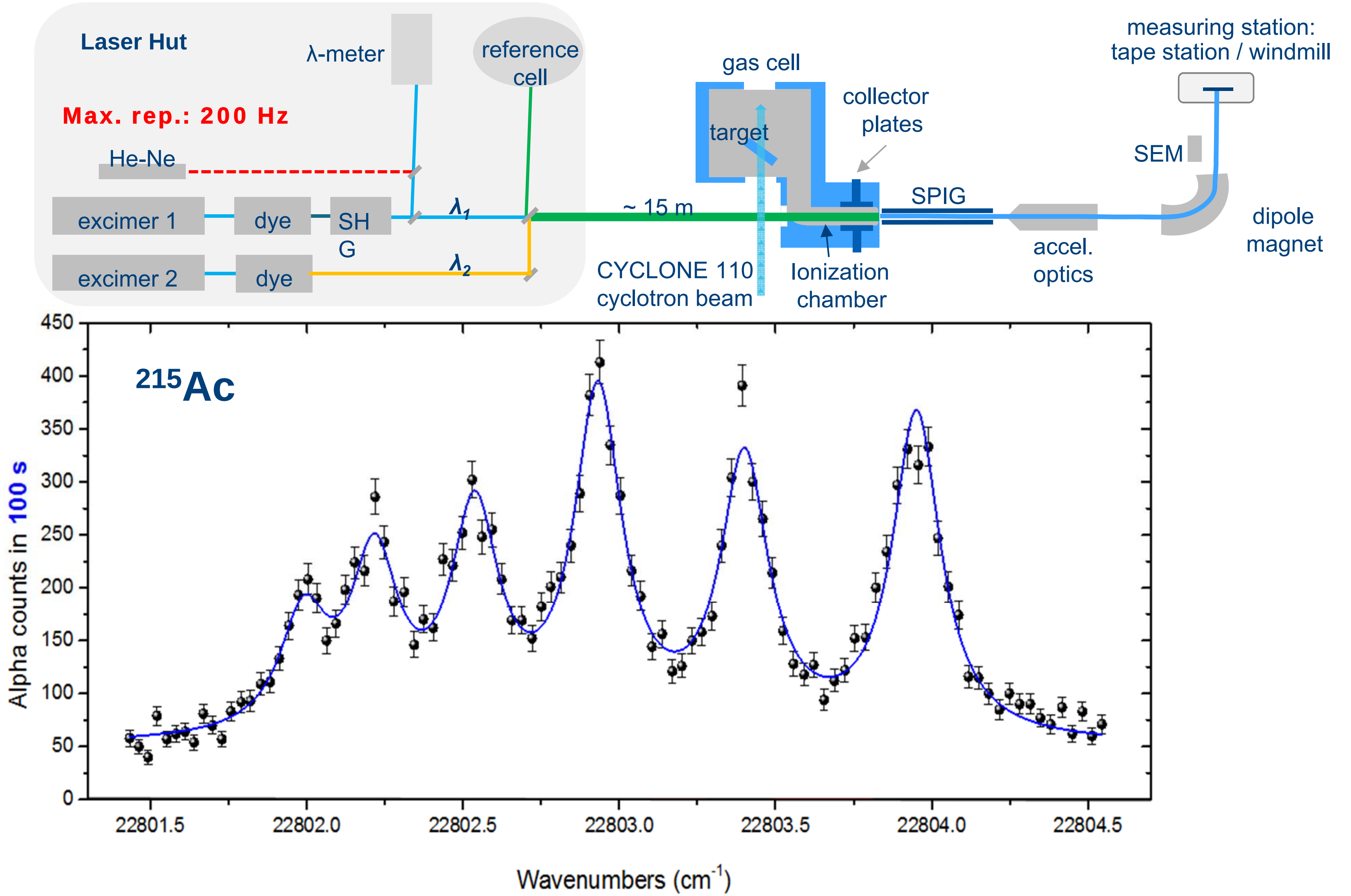
University of Jyväskylä: I. Moore, V. Sonnenschein

ISOLDE: S. Rothe

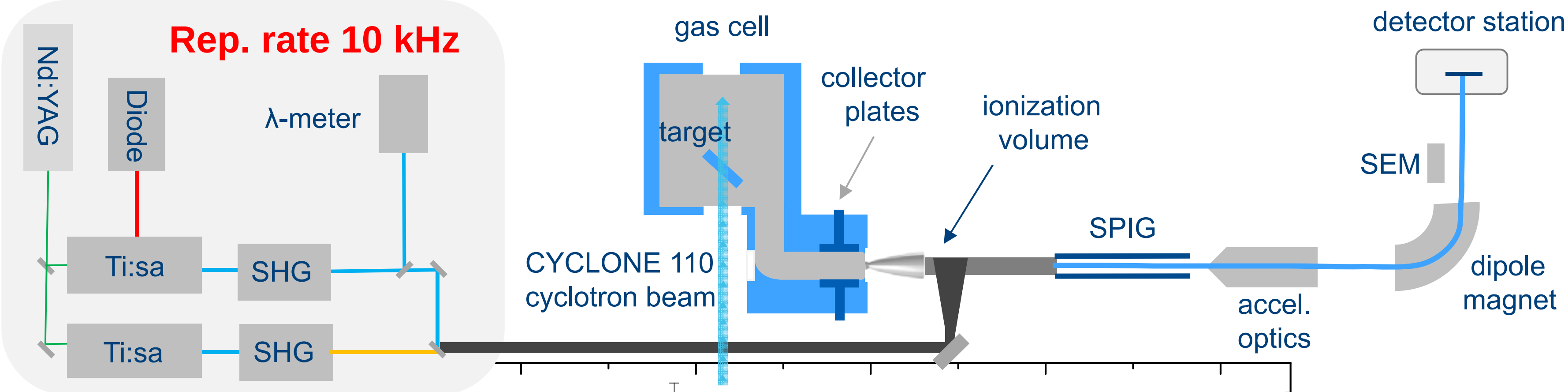
GSI: M. Block, M. Laatiaoui

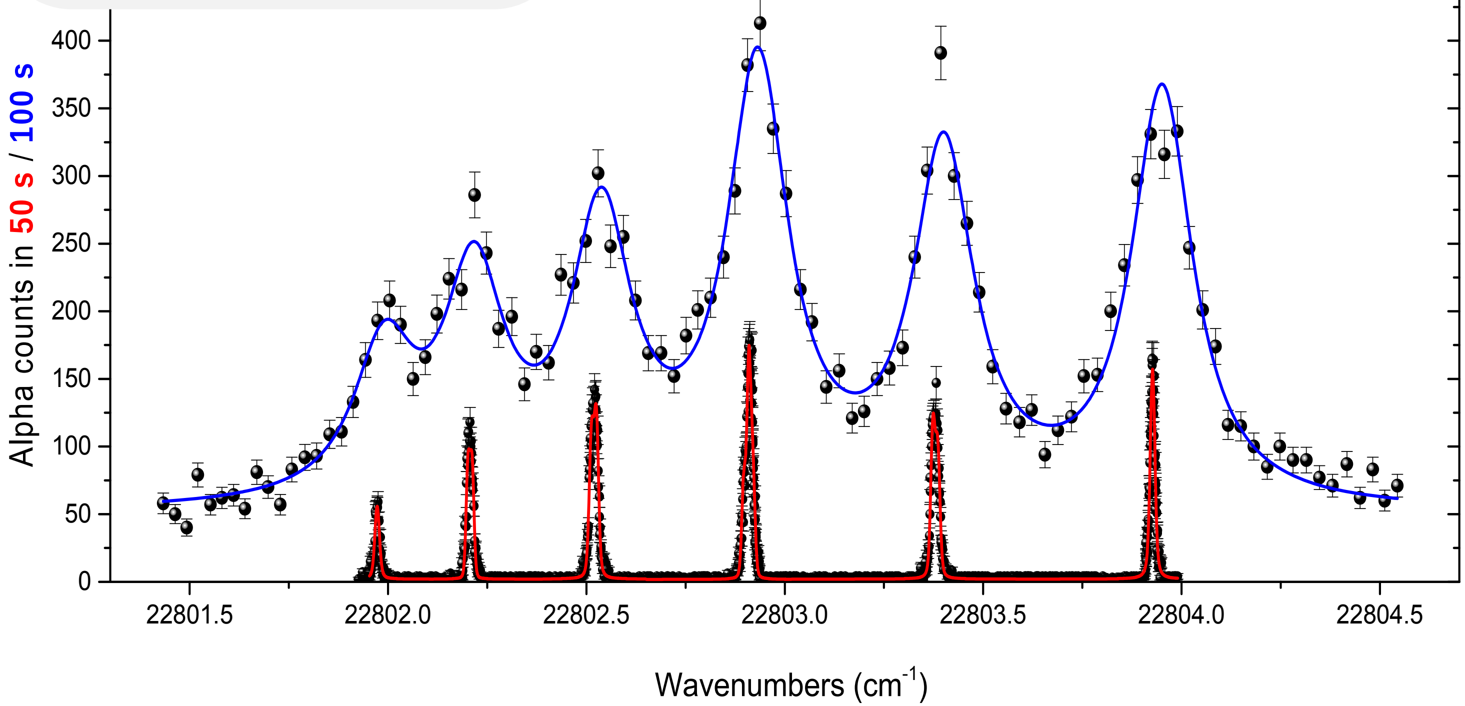
TRIUMF: P. Kunz, J. Lassen, A. Teigelhoefer

Integration: In-Gas-Cell Laser Spectrocopy



Integration: In-Gas-JET Laser Spectrocopy





Figures of merit:

- ✓ FWHM ~ 400 MHz ⬇
- ✓ Selectivity ~ 200 ⬆
- ✓ Efficiency ~ 0.5% ⬆

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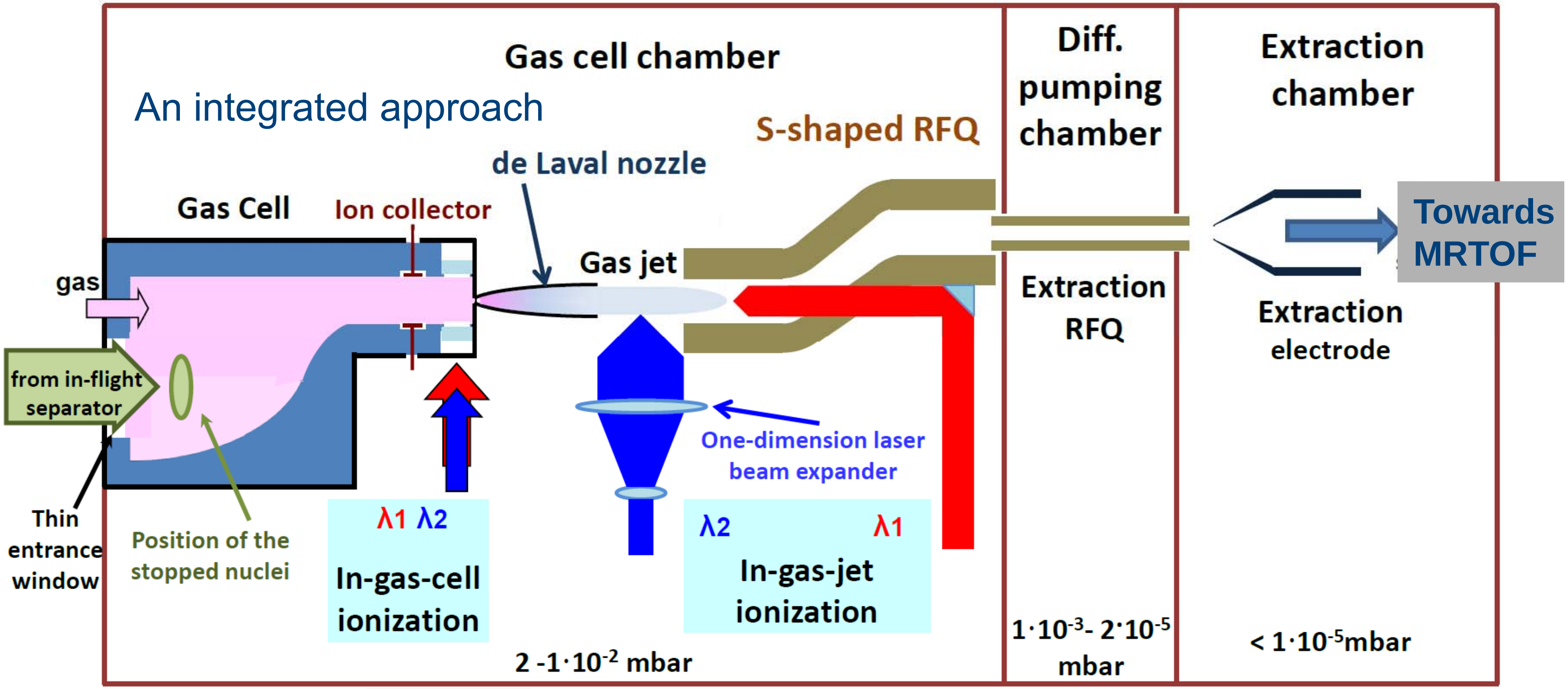
An integrated approach



=> pre-separation by low-energy in-flight separators

=> reaction products stopped in < 500 mbar Ar

=> small cell fast evacuation

⇒ ionization zone shielded from stopping zone

⇒ unwanted ions collected

⇒ broadband in-gas cell ionization to find the resonances

⇒ unwanted ions further collected

⇒ supersonic jet:

*extended atom beam, **low pressure**, **low temperature***

- ⇒ ~ 200 MHZ resolution
- ⇒ laser spectroscopy
- ⇒ Isomeric purification

R. Ferrer et al., NIMB 317 (2013) 570-581 **REGLIS@S³**

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REGLIS^3 @ SPIRAL2

❑ ^{94}Ag

High-spin isomerism ($J=21^+$)

β, β-delayed p, 1p-, and 2-p!? emission

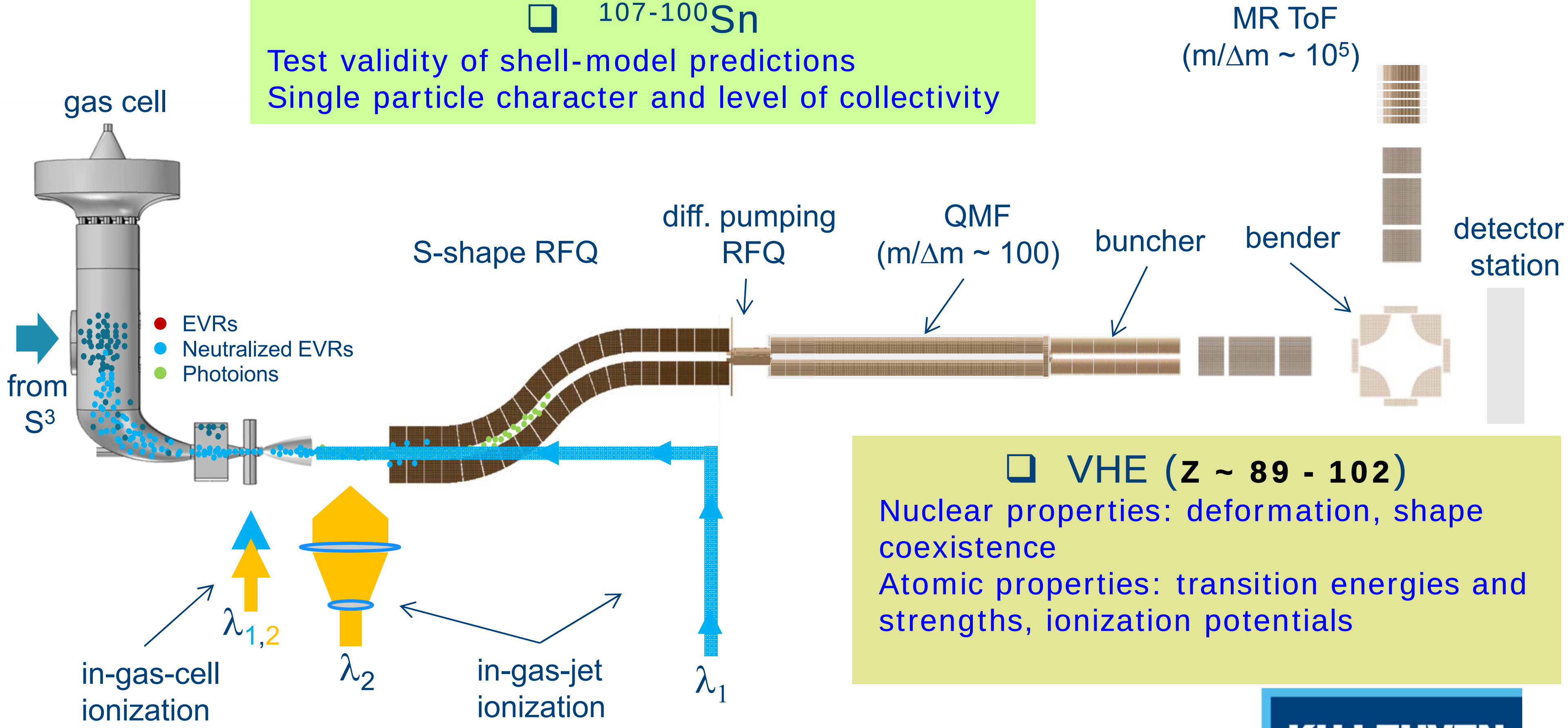
❑ ^{80}Zr

Shape coexistence and single-particle behavior

❑ $^{107-100}$Sn

Test validity of shell-model predictions

Single particle character and level of collectivity



❑ VHE ($Z \sim 89 - 102$)

Nuclear properties: deformation, shape coexistence

Atomic properties: transition energies and strengths, ionization potentials

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REGLIS^3 @ SPIRAL2

MAJOR ASSETS OF THE DEVICE

✓**efficient :**
produced in very small quantities (-> ~ 1 pps*)

✓**selective :**
suppression of unwanted isotopes
(1/10 000 lower limit demonstrated)

✓**fast :**
short life time (up to ~ 40 ms)

✓**sufficient spectral resolution (-> few hundred MHz):**
determine the isotope/isomer shift and hyperfine structure, spin, moments…

=> 2 in 1 : Laser spectroscopy + Laser Ion Source (pure (isomeric) beams)

Expected performances

Transmission through S^3	40-50 %
Thermalization, diffusion and transport through the exit hole	50-90 %
Neutralization	50-100 %
Laser ionization	50-60 %
Transport efficiency	80-90 %
Total efficiency	**4-24 %**

** Rate of ions reaching the detection system*

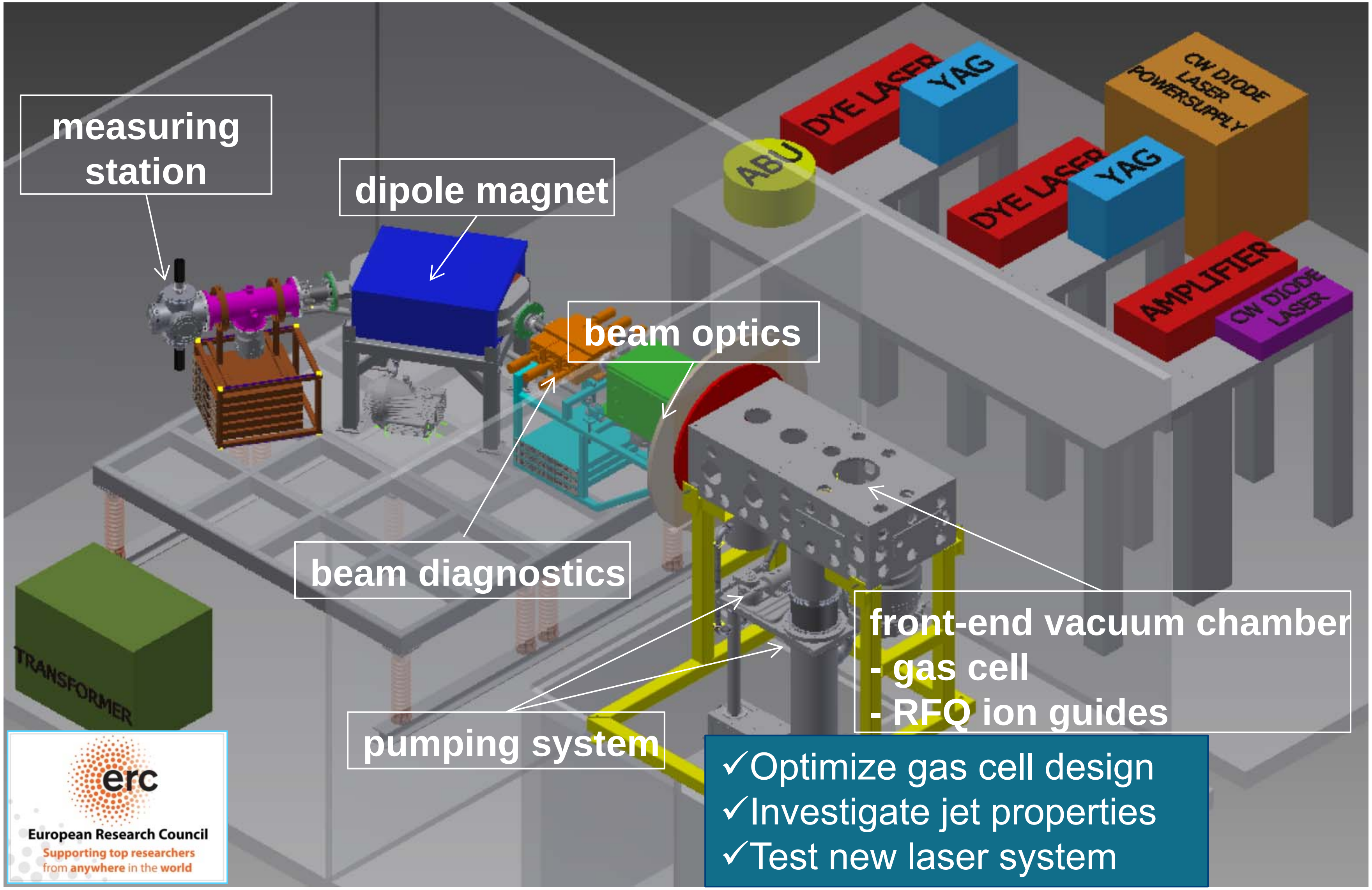
580 R. Ferrer et al. / Nuclear Instruments and Methods in Physics Research B 317 (2013) 570–581

Table 2
Summary of the main results obtained for the three reaction products (first column) taken as a model to study the performance of the IGLIS@**S**^{3} setup. In the second and third columns the rate at the Focal Plane (FP) for the species of interest and the total current, including contaminants, are respectively given. The range in the argon buffer gas of the reaction products, the steady-state plasma density, and the time needed for neutralization are listed in the forth, fifth and sixth columns, respectively. In the last column the expected rate for the species of interest is given taking into account a current of the primary beam of 1 pμA and a lower limit overall efficiency of the system (see Table 1).

Reaction	Rate@FP (pps)	$I_{tot.}$ @FP (pps)	Range (mm)	ρ_{plasma}[a] (cm^{-3})	$\tau_{rec.}$ (ms)	Rate@Detec. (pps)
^{58}Ni (^{40}Ca, p3n)$^{\mathbf{94}}$**Ag**	45	$2{\cdot}10^6$	14	$2{\cdot}10^8$	5	1.5
^{197}Au (^{22}Ne, 4n)$^{\mathbf{215}}$**Ac**	$7{\cdot}10^3$	$1{\cdot}10^4$	9	$1.3{\cdot}10^7$	70	220
^{208}Pb (^{48}Ca, 2n)$^{\mathbf{254}}$**No**	11	50	16	$1.2{\cdot}10^6$	700	0.3

[a] Assuming a recombination coefficient in argon of 10^{-6} cm^3 s^{-1}.

HELIOS @ KU Leuven



✓Optimize gas cell design
✓Investigate jet properties
✓Test new laser system

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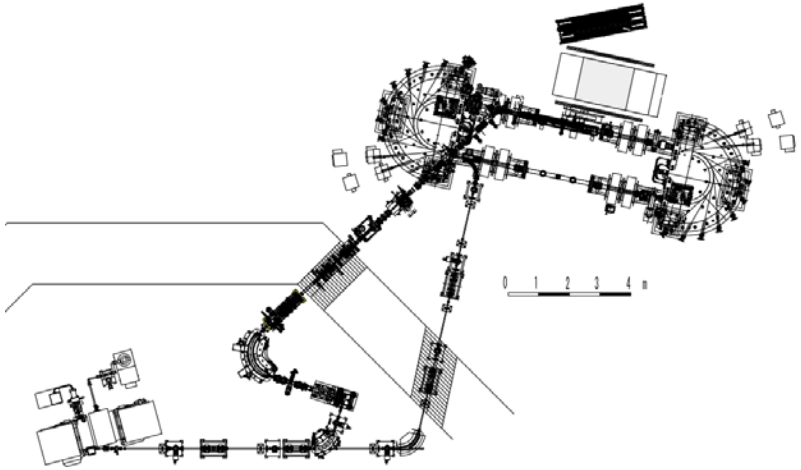
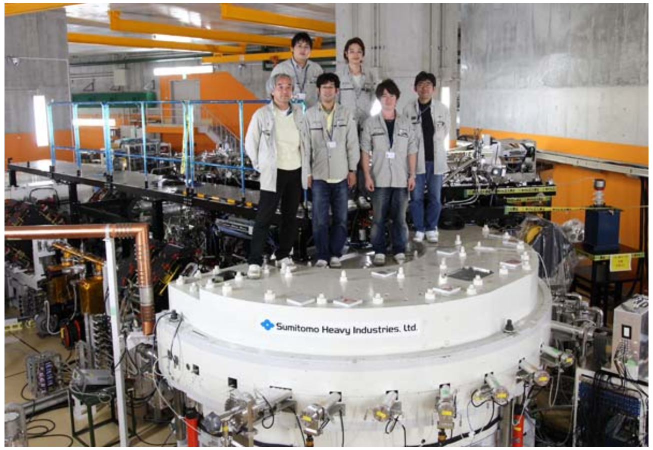
Integration: Coupling to storage rings

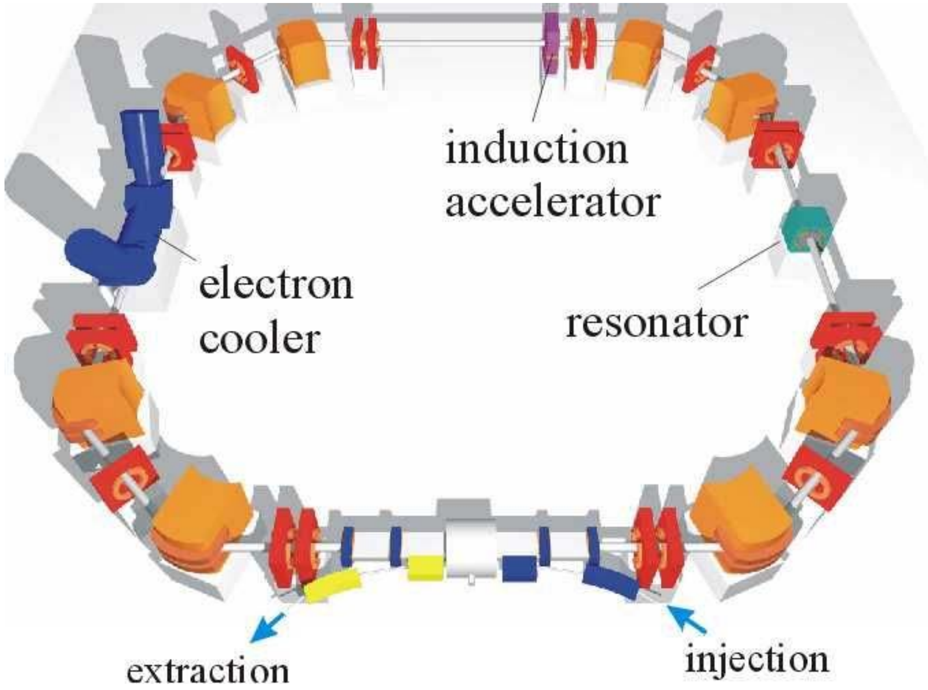
ERIS for SCRIT at RIKEN





M. Wakasugi et al., NIMB 317 (2013) 668-673

TSR@ISOLDE



M. Grieser et al.
Eur. Phys. J. Special Topics 207 (2012) 1–117

Outlook: after half a century still alive and kicking!

An ISOL facility: stopped radioactive nuclei, reaccelerated and mass separated

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